EXTREME TEMPERATURE DESIGN TECHNIQUES FOR A VENUS EXPLORATION S-BAND TRANSMITTER

Robert H. Sternowski

Softronics Ltd., 6920 Bowman Lane NE, Cedar Rapids, IA 52402, USA, Email: bobs@softronicsltd.com

ABSTRACT

Softronics Ltd. was awarded a competitive NASA Small Business Innovation Research (SBIR) contract in 2004 for the analysis, design, and build of a transmitter for a Venus surface explorer craft. The novel aspect of the winning design was the ability of the S-band transmitter to operate continuously in the harsh 465°C, 90 barr CO_2 Venusian atmosphere *without cooling*. The transmitter is built from Silicon Carbide transistors and minimal other components constructed similar to early 20th century radios; no conventional electronic components or organic materials would survive the environment even briefly. This paper chronicles the development path to a successful design.

1. ORIGINS OF THE PROJECT

The Venusian transmitter project began in response to a NASA small business R&D solicitation. Based on prior military experience with new high-temperature Silicon Carbide transistors, as well as Softronics' experience in radio design and development, we set out to devise a strategy to win a competitive design award by offering a novel solution. In reviewing prior art, it was immediately obvious that past Venusian probes relied on a huge pressure vessel with closed cycle cryogenic cooling. The size, weight, and power of such probes were immediately targeted as candidates for a new approach. The strategy that was somehow creatively sparked was to offer a transmitter that would work in that environment without a pressure vessel or cooling system; the electronics would be exposed to and operated at the ambient 465°C atmospheric temperature.

The six-month Phase I study performed an analysis of how our approach would fare in the Venusian environment, along with conducting temperature tests on critical materials, components and circuits. In summary, that study and experimental output showed that our approach was feasible. That study in turn resulted in an invitation to propose a full-scale prototype for a Phase II contract; we did so, and were competitively awarded a second contract to build the prototype. The remainder of this paper describes much of the path travelled to a solution.

2. DESIGN APPROACH

Our primary concern was the environment, and we were given key guidance after contract award, to wit:

- We should design for constant 465°C operating ambient temperature
- We should design for constant 90 barr pressure
- We should design for 97% CO_2 atmosphere
- We should not be concerned with the acid, which is present only on atmospheric entry; the probe will be behind a shroud

After carefully comparing these environmental constraints against our proposed approach, we quickly realized that:

- The 465°C temperature was our primary driver for material selection and thermal design
- The pressure was irrelevant to our design
- The supercritical CO_2 atmosphere was actually beneficial to our cooling scheme
- Lack of acid opened the material choices

Additionally, it appeared that the only reason to have a case for the transmitter was to prevent any type of ambient material (jokingly dubbed "green Venusian slime") from accumulating on the microwave components and degrading their performance via one of a number of high frequency loss mechanisms. Thus it was determined that a closed (using a "leaky" gasket material) but not pressurized protective case was desirable.

Given a valid set of boundary conditions, we planned our effort, and broke it down into discrete tasks:

1. Transmitter architecture
2. Material selection
3. Thermal design
4. Circuit design
5. Component design
6. Environmental test

Each task is discussed in detail in the remainder of this paper.

3. TRANSMITTER ARCHITECTURE

While our original proposal had been based on a 10 watt transmitter at 2.2 GHz (S-band), sufficient to maintain a 50 kbps link to an orbital relay, we were asked to consider how we would build a direct Venus-Earth S-band transmitter with approximately 150 watts output power. Thus we broadened our approach to consider both possibilities, using a variable mix of common radio modules.

Because of the extreme temperature, only Silicon Carbide semiconductors were usable as active devices. Thus we could not build a conventional radio with crystals, frequency synthesizers, filters, etc., because none of those conventional components exist in high temperature forms. So we stepped backward one century to the early days of radio and the techniques of Marconi and other pioneers to find a solution, knowing that they too lacked a selection of sophisticated components. This led us to an old concept of a free-running power oscillator. This was easily implemented with an SiC transistor and a transmission line feedback network, plus two resistors, four capacitors, and three inductors. Testing showed that the frequency accuracy and stability was a function primarily of the [predictable] expansion coefficients of the feedback network, with only minimal impact from the transistors.

Our transistor of choice was the Cree Inc. CRF-24010, one of the few production SiC high frequency MESFETs available on the open market. This device had the frequency response, gain, dissipation, and size that we required. Further research into SiC MESFET characteristics revealed that such SiC devices were capable of high total dose radiation needed to survive the transit to Venus, and up to 1000°C temperatures. However, the commercial device was rated only at more "Earthly" temperatures, and so we undertook a test program to determine the high temperature performance. In summary, we saw 40% of 25°C RF gain at an operating temperature of 600°. This showed that we could expect about 7 decibels (db) of gain, and no more than 2.5 watts output at temperature. Unfortunately the commercial package would not survive, and so we saw that a custom mounting for the die would be required.

Given 2.5 watts output and 7 db of gain, we proceeded to develop an architecture that used two oscillators in a frequency-shift keying (FSK) scheme, one "mark" and the other "space", that would fail "softly" to an On-Off Keying (OOK) modulation scheme in the event that one oscillator failed. To obtain 10 watts output for an orbital relay, a number of 2.5 watt amplifiers were cascaded and combined with passive hybrid couplers to a single antenna output. To obtain 150 watts output, many more amplifiers were used in a classical hybrid "tree". While this at first looked unbelievably complex, we gradually realized that the fail-soft nature of this architecture, coupled with the very low parts count and ruggedness of the simple components, actually made it a simple and attractive approach. We now had to proceed to the next level of detailed design to determine HOW we were going to implement our system design.

4. MATERIAL SELECTION

The first implementation problem was determining what materials would survive the 465°C ambient. A great deal of research, and a significant pile of incinerated or melted materials from our lab furnace, revealed some simple truths:

- No organic materials would survive.
- Glass and ceramic were the only two usable insulating materials.
- Our metal choices were limited to select metals: copper and alloys, iron and alloys, gold, silver. Lightweight metals would fatigue at high temperatures.
- Electrical connections would have to be mechanical, welded, brazed, silver-soldered, or eliminated (single-piece multi-component)

Given that we required resistors, capacitors and inductors, some ingenuity would be required, and led us back to Marconi once again. Our structural needs would be met by the allowable materials.

5. THERMAL DESIGN

The next problem was to determine how we could "cool" our transistor to the ambient 465°C, given that we could stand 30-40°C rise in junction temperature. The problem turned out to be a complex fluid problem, owing to the supercritical CO_2 atmosphere. We started out using ANSYS for modelling and design, and evolved to a software heatsink model called "NATSINK" by Dr. Ake Malhammar. With Dr. Malhammar's assistance, the software was tailored to the high pressure environment from its normal Earth ambient. The Aerospace Engineering Department at Iowa State University calculated the CO_2 fluid constants for our temperature and pressure, and when plugged into NATSINK, allowed us to model the thermal performance of various configuration heatsinks and dissipations in a simulated Venusian environment.

The output of the thermal design was not unexpected: we needed to conduct the heat rapidly out of the 1 square millimeter SiC die to a sufficient dissipating area. To do this, we needed high thermal conductivity materials for our heatsink. At our temperatures, that left only diamond, Silicon Carbide, Copper, and Silver. Silver and Copper are very close in conductivity, thus Copper was the winner in that pairing due to cost. Silicon Carbide was no better than Copper, and far more difficult to work with. Many of our heatsink analyses focused on diamond, and even coating a ceramic heatsink with diamond (which is easily done today). We were very disappointed to find that, at 465°C, diamond's thermal conductivity degraded to about that of Copper due to shifts in the crystalline structure with temperature. Thus we used Copper for our heatsink material, with black finish for black body radiation. Fig. 1 shows the modular heatsink design, swirled for structural strength. Electronic modules are mounted to the inside vertical rim onto the fin bases.

A key secondary thermal problem to be solved was attaching the SiC transistor die to the heatsink (none of the other components had any significant thermal issues). Conventional solder attach was grossly insufficient, with a limit of 250-300°C. We turned to Dr. R. Wayne Johnson, Auburn University, for help, and in summary, he developed an alternate die attach braze process that would survive up to at least 515°C. We are proceeding with this solution, with implementation and test planned in 2007.

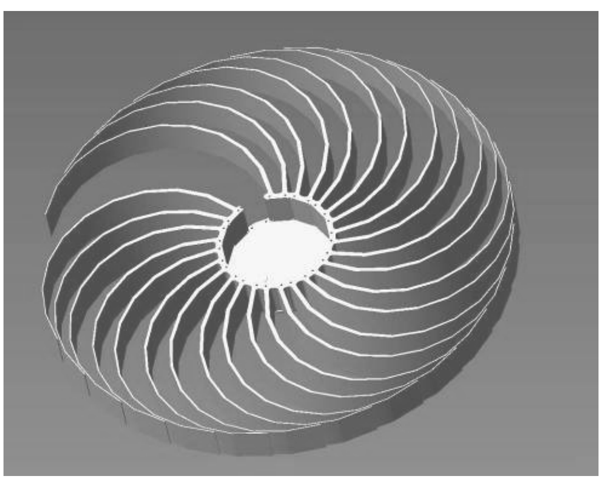

Fig. 1 – "Galaxy" Heatsink Design Has Circuit Boards Mounted On Inside Vertical Rim, With Interconnecting Power and Radio Quadrature Hybrids On A Top And Bottom Cover Disk

6. CIRCUIT DESIGN

From our system architecture design, we saw that the entire transmitter could be implemented with a series of 2.5 watt amplifier modules interspersed with quadrature combiners (also used as splitters). The oscillators were the common 2.5 watt amplifier module with a feedback network added, but were essentially the same design. Thus our effort focused on efficiently designing a common amplifier module and a quadrature combiner.

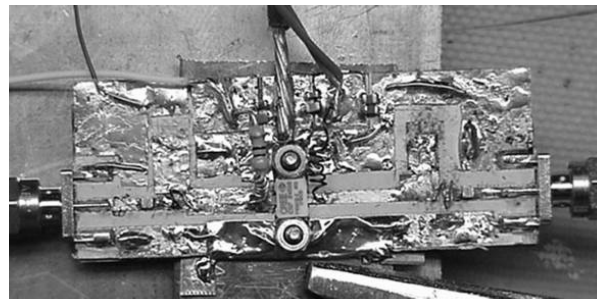

Fig. 2 – High Temperature 2.5W Amplifier Prototype

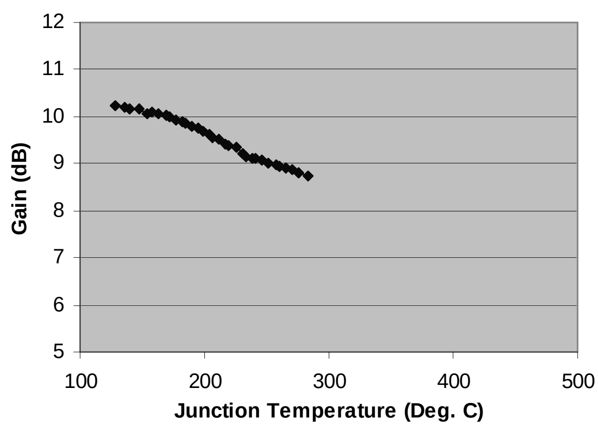

Fig. 3 – Gain vs Temperature Testing of Fig. 2 Amplifier

The amplifier circuit, after considerable modelling and experimentation, was selected to be a standard grounded-source MESFET amplifier. To improve DC power efficiency by approximately 100%, a negative grid bias (used as the keying signal) was selected in lieu of self-bias (e.g., a source resistor). To that circuit were added the necessary resistors, capacitors and inductors—approximately ten components per amplifier. Each amplifier or oscillator was to be implemented on a single ceramic circuit board.

The quadrature combiners/splitters were also extensively analyzed, and found to be easily implemented as metallised traces on a ceramic circuit board, requiring no discrete components.

Fig. 2 shows one of our later breadboard amplifiers, and Fig. 3 the gain versus temperature test results. The final form amplifiers and oscillators will be built in 2007.

7. COMPONENT DESIGN

Our inspiration for component design was Marconi and his early transmitters. Given our limited material selection, we quickly converged on the following approaches:

- Resistors: either nichrome wire or fired ceramic paste wafers were buildable and survivable, and could be welded or brazed onto the ceramic circuit board; only two per amplifier were needed
- Capacitors: parallel plates or interdigitated fingers implemented as metallised traces on a ceramic circuit board were sufficient and easily implemented
- Inductors: at 2.2 GHz, inductors were simply transmission line metallised traces on our ceramic circuit boards

Wire used for power connections is fibreglass insulated copper. Coaxial cable—a unique problem—was designed by the project using copper semi-rigid 0.141 inch diameter cable but with the Teflon dielectric replaced by glass beads. Similarly, special high temperature SMA coaxial connectors were hand-built by replacing the Teflon dielectric insulator inserts with castable Aremco 586 ceramic.

8. SIMULATED VENUS TEST ENVIRONMENT

One of the key identified issues in the early stages of this project was just how we were going to prove the system would work in the actual [simulated] Venusian environment. The combination of temperature and pressure, plus supercritical CO_2, posed an interesting challenge. Once again, we turned to Iowa State University for assistance, and Dr. William Byrd, Director of NASA's Iowa Space Grant Consortium (ISGC, of which Softronics Ltd. is an industrial affiliate) came up with a novel and simple solution. Using the Ideal Gas Law, he observed that if we filled a sealed chamber with CO_2 at 25°C and 535 psi, then raising the temperature to 465°C would result in a pressure of 90 barr, equal to the Venusian pressure. Problem solved, neatly and simply.

With this solution in mind, we searched and found a small, used chemical reactor made by Autoclave Engineers that was capable of sustaining both the pressure and temperature simultaneously. The ISGC was awarded a subcontract to refit the chamber, instrument it, and conduct the final environmental tests on our transmitter circuits using this scheme.

Final testing will be done in the simulation chamber, although most of our testing is done in a laboratory furnace since pressure has little impact on our design.

9. SUMMARY

The high temperature Venus telemetry transmitter is well along in its design cycle. A significant number of material and architecture issues have been solved enroute to the final design, all using novel combinations of new technology and century-old radio construction techniques. The result will be a high temperature transmitter operating in the Venusian ambient that is directly heatsunk to the 465°C CO_2 atmosphere. Architectures for both orbital relay and direct Venus-Earth links have been developed, and are implementable with common modules.

The resulting extreme environment transmitter design and techniques are applicable to other applications, including general radio and circuit design in both hot and cold planetary probes, and military/commercial terrestrial applications in extreme environments.

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